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WAVELENGTH DIVISION AND POLARIZATION DIVISION MULTIPLE
ACCESS FREE SPACE OPTICAL TERMINAL USING A SINGLE APERTURE

RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No.
5 60/422,185, filed on October 29, 2002. The entire teachings of the above application
are incorporated herein by reference.

GOVERNMENT SUPPORT

The invention was supported, in whole or in part, by a grant Contract No.
F19628-00-C-002 from USAF (Program 26). The Government has certain rights in the
10 invention.

BACKGROUND OF THE INVENTION

This invention is related to communication methods and devices using electro-
magnetic waves and has particular application to optical communications in free space.
The growing interest in dynamic and rapidly deployable free space optical
15 communication links is combined with efforts to increase traffic throughput, implement
sophisticated networking capabilities for intelligent routing of data, and widen the utility
of optical terminals. Multi-channel approaches can meet these demands, in particular
through the use of wavelength division multiplexing (WDM). There are several
advantages to WDM that justify its role in free space optical communications. WDM is

well established in the 1.5 μm wavelength band, primarily due to availability of erbium amplifiers, and this wavelength range meets eye safety requirements. Furthermore, the necessary components for WDM already exist and growth in terrestrial communications has driven down their prices. In addition, WDM fiber systems are well understood, and
5 this knowledge relates directly to free space WDM systems.

SUMMARY OF THE INVENTION

A method and communication device embodying this invention allow several deflectors to share the same aperture device, which may be a telescope. These deflectors are used to steer the signals carried by electromagnetic waves into and out of
10 the communication device. These deflectors may be combined into one or more stacks for more efficient use of the hardware. To allow such stacking of deflectors, some deflectors, while deflecting the signals steered by them, are at the same time transparent for signals steered by some other deflectors in the same stack. The deflective properties of the deflectors may vary with the angle at which they are positioned in the course of
15 steering, for this reason rather than a single frequency, each deflector may be assigned a wavelength band. This wavelength band may be made narrower if the electromagnetic waves impact the deflectors at a nearly normal angle. Each deflector may handle both the transmitted and received signals coming to and from the same direction. When two stacks of deflectors are used, it may be advantageous to intermesh the wavelength bands
20 used by the deflectors in each stack. Further separation of signals within the device is achieved with beam splitters in combination with quarter wave plates and/or Faraday rotators. The deflectors may be transmissive or reflective.

The present invention provides a communication device, which may comprise an aperture structure and deflectors deflecting respective electromagnetic signals of
25 respective wavelengths at respective angles, the electromagnetic signals passing through the aperture structure. Such device may further comprise an aperture linear/circular polarization device between at least one of the deflectors and the aperture structure. Some deflectors may be movable. The deflectors may form a stack, where at least one

deflector in the stack passes a signal deflected by another deflector in the stack. The individual deflectors in the stack may pass signals deflected by other deflectors in the stack. The individual deflectors in the stack may deflect substantially all signals each within its respective non-overlapping wavelength band. Some deflectors in the stack may reflect signals at nearly normal incidence. The deflectors in the stack may be reflectors. The device may also comprise a second stack of deflectors with similar properties sharing the same aperture structure. Second stack deflectors' wavelength bands may be intermeshed with first stack deflectors' wavelength bands, i.e., at least one second stack deflectors' wavelength band is located between two first stack deflectors' wavelength bands and at least one first stack deflectors' wavelength band is located between two second stack deflectors' wavelength bands. Such device may employ a polarization beam splitter coupled to the aperture structure and the first stack, a signal path coupled to the polarization beam splitter, and a linear/circular polarization device or a polarization rotation device, positioned so that electromagnetic signals deflected by at least one of the deflectors in the first stack, are deflected at nearly normal angle, are linearly polarized when leaving and entering the polarization beam splitter, and, before being deflected, first pass through the polarization beam splitter and then pass through the linear/circular polarization device and, after being deflected, first pass through the linear/circular polarization device and then pass through the polarization beam splitter, the deflectors in the first stack being reflectors. Such device may further comprise a transmission path and a reception path, the signal path receiving from the transmission path at least one signal carrying communications transmitted by the device and the reception path receiving from the signal path at least one signal carrying communications received by the device, the electromagnetic signals deflected by at least one of the deflectors in the first stack carrying communications transmitted by the device and communications received by the device. Such device may further comprise a second stack of deflectors deflecting respective electromagnetic signals passing through the aperture structure at respective angles, the individual deflectors in the first stack passing signals deflected by other deflectors in the first stack and individual

deflectors in the second stack passing signals deflected by other deflectors in the second stack, the deflectors in the second stack being reflectors; and a second linear/circular polarization device, positioned so that electromagnetic signals deflected by at least one of the deflectors in the second stack, are deflected at nearly normal angle, are linearly polarized when leaving and entering the first polarization beam splitter, and, before being deflected, first pass through the first polarization beam splitter and then pass through the second linear/circular polarization device and, after being deflected, first pass through the second linear/circular polarization device and then pass through the first polarization beam splitter, the direction of polarization of the electromagnetic signals passing through the first linear/circular polarization device being substantially orthogonal, within the signal path, to the direction of polarization of the electromagnetic signals passing through the second linear/circular polarization device. Such device may further comprise a second polarization beam splitter coupled to the signal path; a first transmission path; a first reception path; a second transmission path; a second reception path; a first polarized path coupled to the second polarization beam splitter; the first polarized path receiving from the first transmission path at least one signal carrying communications transmitted by the device and the first reception path receiving from the first polarized path at least one signal carrying communications received by the device; and a second polarized path coupled to the second polarization beam splitter; the second polarized path receiving from the second transmission path at least one signal carrying communications transmitted by the device and the second reception path receiving from the second polarized path at least one signal carrying communications received by the device. In such device electromagnetic signals deflected by at least one of the deflectors may carry communications transmitted by the device and communications received by the device and the aperture structure may be a telescope.

An embodiment of this invention may also be a device for deflecting electromagnetic waves comprising a first deflector deflecting electromagnetic waves within a first wavelength band and passing electromagnetic waves within a second wavelength band and a second deflector deflecting electromagnetic waves within a

second wavelength band, the second deflector positioned to receive the electromagnetic waves passed through the first deflector.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

10 Fig. 1 shows the functioning of a quarter wave plate (QWP).

Fig. 2 shows the functioning of a 45 degree Faraday rotator (FR).

Fig. 3 shows the functioning of a half wave plate (HWP).

Fig. 4 shows the functioning of a directional rotation module (DRM).

15 Fig. 5 is a diagram showing the general functioning of an embodiment of this invention.

Fig. 6 shows an embodiment of this invention.

Fig. 7 shows the functioning of a single stack of reflective deflectors used in some embodiments of this invention.

20 Fig. 8 shows the functioning of two stacks of reflective deflectors used in some embodiments of this invention.

Fig. 9 shows the dependence of the reflective deflectors' passbands on the angle of incidence.

Fig. 10 shows the functioning of a holographic optical element.

Fig. 11 shows an embodiment of this invention using a single stack of deflectors.

25 Fig. 12 shows an embodiment of this invention using two stacks of deflectors.

Fig. 13 shows an embodiment of this invention with additional details.

Fig. 14 illustrates some uses of directional rotation modules in some embodiments this invention.

DETAILED DESCRIPTION OF THE INVENTION

A description of preferred embodiments of the invention follows.

Some embodiments of the present invention include at least one linear/circular polarization device with two terminals also known in the art as a quarter wave plate (QWP). Such devices may be used to convert incoming circularly polarized electromagnetic waves into linearly polarized electromagnetic waves and convert incoming circularly polarized electromagnetic waves into linearly polarized electromagnetic waves. A variety of such devices is known in the pertinent art.

Fig. 1 schematically shows the functioning of a QWP 75 where the directions of linear polarization (S and P) of electromagnetic waves entering and leaving the QWP 75 are shown as 71 and 72 and the directions of circular polarization (left hand circular (LHC) and right hand circular (RHC)), as defined by the Institute of Electrical and Electronics Engineers, are shown, respectively, as 74 and 73.

In some types of quarter wave plates, the correspondence between the directions of linear polarization and of circular polarization is determined by the orientation of so called "slow" and "fast" axes shown in Fig. 1 as 78 and 79 respectively.

The functioning of a QWP 75, as pertinent to this invention, can be briefly summarized as following:

An incoming wave that is linearly polarized within the plane S 71 on QWP terminal A 76 produces on QWP terminal B 77 an outgoing wave that is RHC polarized 74.

An incoming wave that is linearly polarized within a plane P 72 (P being orthogonal to the plane S) on QWP terminal A 76 produces on QWP terminal B 77 an outgoing wave that is LHC polarized 73.

An incoming wave that is RHC polarized 74 on QWP terminal B 77 produces on QWP terminal A 76 an outgoing wave that is linearly polarized within S 71.

An incoming wave that is LHC polarized 73 on QWP terminal B 77 produces on QWP terminal A 76 an outgoing wave that is linearly polarized within P 72.

Some embodiments of the present invention include at least one 45 degree Faraday rotator (FR). Such two terminal devices may be used to rotate the polarization plane of the incoming linearly polarized light by a set amount in the same direction regardless of the terminal the wave enters. A variety of such devices is known in the
5 pertinent art.

Fig. 2 schematically shows the functioning of a FR 95 designed to produce 45 degree rotation where the directions of linear polarization of electromagnetic waves entering and leaving the FR 95 are shown as 91-94.

The functioning of a FR 95, as pertinent to this invention, can be briefly
10 summarized as following:

An incoming wave that is polarized within any plane PA_{in} 91 on FR terminal A 96 produces on FR terminal B 97 an outgoing wave polarized within a plane PB_{out} 94 which is rotated by 45 degrees to PA_{in} .

An incoming wave that is polarized within any plane PB_{in} 93 on FR terminal B
15 97 produces on FR terminal A 96 an outgoing wave polarized within a plane PA_{out} 92 which is rotated by 45 degrees in the same direction to PB_{in} as PB_{out} is to PA_{in} .

The principal properties of a FR, as pertinent to this invention, are the following:

An increment in the angle of PA_{in} produces the same increment in the angle of PB_{out} . An increment in the angle of PB_{in} produces the same increment in the angle of
20 PA_{out} . If PB_{in} is PB_{out} , PA_{in} and PA_{out} are orthogonal. If PA_{in} is PA_{out} , PB_{in} and PB_{out} are orthogonal.

Some embodiments of the present invention include at least one half wave plate (HWP). Such two-terminal devices may be used to reflect the polarization plane of an incoming linearly polarized electromagnetic wave about a so-called fast axis. A variety
25 of such devices is known in the pertinent art.

Fig. 3 schematically shows the functioning of a HWP 25 with the fast axis 30 where the directions of linear polarization of electromagnetic waves entering and leaving the HWP 25 are shown as 26-29.

The functioning of a HWP, as pertinent to this invention, can be briefly summarized as following:

5 An incoming wave that is linearly polarized within a plane 26 (at a 67.5 degrees angle to the fast axis 30) on HWP terminal A 31 produces on HWP terminal B 32 an outgoing wave that is polarized within the plane 28 at 45 degrees to the original plane 26.

An incoming wave that is linearly polarized within a plane 28 on HWP terminal B 32 produces on HWP terminal A 32 an outgoing wave that is polarized within the plane 26.

10 An incoming wave that is linearly polarized within a plane 27 (at a 22.5 degrees angle to the fast axis 30) on HWP terminal A 31 produces on HWP terminal B 32 an outgoing wave that is polarized within the plane 29 at 45 degrees to the original plane 27.

15 An incoming wave that is linearly polarized within a plane 29 on HWP terminal B 32 produces on HWP terminal A 31 an outgoing wave that is polarized within the plane 27.

Some embodiments of the present invention include at least one directional rotation module (DRM). Fig. 4 shows the operation of a DRM 40 implemented as a combination of a HWP 49 with its fast axis 351 and a FR 50. Arrows 41-48 show the direction of polarization of linearly polarized electromagnetic waves entering and leaving the DRM 40. Linear polarization planes represented as arrows 41, 42, 44, and 47 are at a 67.5 degrees angle to the fast axis 351. Linear polarization planes represented as arrows 43, 45, 46, and 48 are at a 22.5 degrees angle to the fast axis 351. The DRM 40 allows linear polarization to be rotated 90 degrees when electromagnetic waves travel in one direction and to stay unchanged when they travel in the opposite direction.

Some embodiments of the present invention include at least one polarization beam splitting device or polarization beam splitter (PBS). A variety of such devices is known in the pertinent art. The functioning of one type of PBS, as pertinent to this

invention, can be briefly summarized as following: PBS reflects at some non-zero angle electromagnetic waves linearly polarized within plane P1 and is transparent to electromagnetic waves linearly polarized within plane P2, P2 being orthogonal to P1.

Fig. 5 schematically shows functioning of an embodiment of this invention. The device 3 transmits electromagnetic signals 1 and receives electromagnetic signals 2 via a single aperture structure 4. The aperture structure 4 allows transmission and receiving of electromagnetic waves 5, 6 from and to multiple directions and with multiple wavelengths λ . The directions of electromagnetic waves 5, 6 can be changed using steerable deflectors within the device 3.

Fig. 6 shows a specific embodiment of the device 3 of Fig. 5. The dotted lines show the path traveled by electromagnetic waves carrying signals.

In this embodiment of the invention, the aperture device 4 is a large field of view off-axis afocal telescope. It stands between the optical paths of incoming and outgoing signals outside the device 101 and inside the device 102. These signals are carried by circularly polarized electromagnetic waves. Along the optical path 103 between QWP 19 and PBS 21, the signals are linearly polarized. QWP 19 is responsible for the conversion of circularly polarized signals into linearly polarized signals and vice versa, and any linear/circular polarization device performing this function may be used in this position. For left-hand and right-hand circular polarizations on 102, the corresponding directions of linear polarization on 103 are perpendicular. The PBS 21 is positioned so that it is transparent to signals on 103 polarized along one direction, so that these signals travel along 104, and reflects the signals with perpendicular polarization so that they travel along 105.

If in positions 14 and 18 the embodiment employs QWPs or any linear/circular polarization devices, the signals on 107 and 108 are circularly polarized before they impact one of the deflectors 61-68, and they are circularly polarized in the opposite direction after the deflection. After reentering the QWPs in the opposite direction, these signals are converted back into linearly polarized signals, but the direction of the polarization is orthogonal to the original direction, so that a signal for which the PBS 21

was transparent ends up being reflected on PBS 21, and vice versa. The functioning of the deflectors 61-68 will be explained below.

Instead of a QWP, the embodiment shown on Fig. 6 may employ a FR in positions 14 and/or 18 to the same overall effect. The polarization planes of linearly polarized signals on 107 and 108 are rotated by 45 degrees before the signals impact one of the deflectors 61-68. After reentering the FR in the opposite direction, the polarization planes of these signals are further rotated by 45 degrees and end up being polarized in the direction orthogonal to the original direction, so that a signal for which the PBS 21 was transparent ends up being reflected on PBS 21, and vice versa.

10 Therefore, the embodiment on Fig. 6 provides the following paths for signals leaving the device through the aperture 4:

Path segment 106 to PBS 21 to path segment 105 to QWP or FR 14 to path segment 108 to one of the deflectors 61-64 to path segment 108 to QWP or FR 14 to path segment 105 to PBS 21 to path segment 103.

15 Path segment 106 to PBS 21 to path segment 104 to QWP or FR 18 to path segment 107 to one of the deflectors 65-68 to path segment 107 to QWP or FR 18 to path segment 104 to PBS 21 to path segment 103.

Both of these paths can also be traversed in the opposite direction for signals entering the device through the aperture 4.

20 If, as in some embodiments, the deflectors 61-68 are used to direct two signals each (received and transmitted), the embodiment on Fig. 6 then may handle up to 16 independent signals traveling to and from 8 different directions. These reflectors may be movable to allow steering of signals in different directions outside the device or fixed for a set of predetermined directions of communications. The movement of the reflectors may be achieved by placing each detector in a electronic motor-controlled mount that can steer the deflected beam in at least the two directions of pitch and yaw.

25 Note that the path segment 106 carries all the signals handled by the device and therefore it will be referred to as "signal path". Note also that within the signal path 106

the direction of polarization of signals passing through QWP or FR 18 is substantially orthogonal to the direction of polarization of signals passing through QWP or FR 14.

The signals on the signal path 106 may be separated using the PBS 22 and further separated so that the transmission paths 109 and 111 carry signals $T_{1,3,5,7}$ and $T_{2,4,6,8}$ for transmission by the device (shown as 1 in Fig. 5) while the reception paths 110 and 112 carry signals $R_{1,3,5,7}$ and $R_{2,4,6,8}$ received by the device (shown as 2 in Fig. 5).

The embodiment shown on Fig. 6 uses reflective wavelength selective reflectors in the role of deflectors 61-68. The functioning of these reflectors as deflectors is illustrated on Figs. 7 and 8. They may be used to steer the signals as they enter and leave the device and each deflector 61-68 may handle signals transmitted to and received from the same direction via the aperture device 4. The arrangement of deflectors 61-68 as two stacks 61-64 and 65-68 permits sharing of the of the aperture 4 and of other elements within the device by several signals. Deflectors 64 and 68 may be referred to as front deflectors, while deflectors 61 and 65 may be referred to as back deflectors.

Fig. 7 shows the properties of wavelength selective reflectors as used in an embodiment of the invention.

The horizontal axis for the graphs 161-164 represents the wavelength. The vertical axis for graphs 161-164 represents the reflectivity of the respective reflector at those wavelengths (high value indicating reflection, low value indicating transmission). Graphs 161-164 show, for reflectors 61-64, the reflectivity at normal incidence as solid lines. The dashed lines represent the reflectivity at the maximal angle of incidence used in the shown embodiment of the invention, i.e. when the given reflector is steered to the maximal angle with respect to the path segment 105.

The wavelength selective reflector reflects some electromagnetic waves and is transparent for all wavelengths used by signals steered by the wavelength selective reflectors behind it. If a movable wavelength selective reflector is transparent for different wavelengths depending on the angle of their incidence on the wavelength

selective reflectors, the reflector at all its positions should reflect the electromagnetic waves steered by it and stay transparent for the signals that are handled by the reflectors behind it. For example, the wavelength selective reflector 63 at all its positions is transparent for transmitted signals T4 and T2 and for received signals R2 and R4

5 handled by reflectors 61 and 62, respectively. The reflector 61 does not have to be transparent for any wavelength. Note that in this embodiment, the same reflector is used to receive and transmit signals from and to the same direction.

As can be seen, the functioning of the stack of reflectors 61-64 is unaffected by the motion of the reflectors despite the change in their reflective properties.

10 This design may be extended for two stacks of deflectors as shown on Fig. 8 which is analogous to Fig. 7 but shows the allocation of spectrum between two stacks of four deflectors each.

The horizontal axis for the graphs 165-168 represents the wavelength. The vertical axis for graphs 165-168 represents the reflectivity of the respective reflector at those wavelengths (high value indicating reflection, low value indicating transmission).
15 Graphs 165-168 show, for reflectors 65-68, the reflectivity at normal incidence as solid lines. The dashed lines represent the reflectivity at the maximal angle of incidence used in the shown embodiment of the invention, i.e. when the given reflector is steered to the maximal angle with respect to the path segment 104. The wavelengths T2, T4, T6, T8, R2, R4, R6, and R8 together with shaded areas around them correspond to the
20 wavelengths and wave bands allocated to the stack 61-64 as shown in Fig 7.

The interleaved structure of wave bands used by stacks 61-64 and 65-68 allows efficient utilization of the available spectrum. The usage of a relatively narrow spectrum for operation of an embodiment of the invention may be beneficial for
25 example in cases when some of the components used in the embodiment (such as HWP or QWP) operate properly only within such a narrow spectrum.

Fig. 9 illustrates the properties of bandpass optical filters that may be used as a part of a wavelength selective reflectors 61-68 used as deflectors in some embodiments. A conventional narrow bandpass interference filter contains alternating dielectric thin

film layers constructed of high and low index media. These filters rely on Fabry-Perot effects, and the optical path length through the individual dielectric layers plays a key role in determining the spectral characteristics of the filter. When the angle of incidence changes, this alters the effective path length through the layers, thus modifying the center wavelength of the filter. Moving away from normal incidence causes such a filter to experience a shift to shorter wavelengths in its center wavelength because the round trip path length for constructive and destructive interference shortens.

For a multilayer dielectric structure, an incident plane wave sees an effective index n_{eff} that can be approximated by the average index within the structure. The effective index can be used to determine macroscopically how a plane wave would interact with the medium under Fresnel reflections and transmissions. This abstraction provides a means of predicting how the center wavelength of the filter, $\lambda(\theta)$, varies as a function of angle of incidence, θ . This angle dependence follows the formula:

$$\lambda(\theta) = \lambda_{\theta=0} \cos(\theta/n_{\text{eff}})$$

For conventional dielectric narrowband filters, n_{eff} is typically approximately between 1.5 and 1.8. For higher index materials one can obtain values of 3.2 and greater using, for example, III-V semiconductor materials, such as GaAs/AlGaAs or InGaAs/AlAsSb. A plot of the change in center wavelength, $\delta\lambda$, as a function of the angle of incidence is shown in Fig. 8 for different n_{eff} values. One can use Snell's law to understand that a high index material will bend light more towards the normal than a low index material; this concept extends to the case here, where an effective index describes Fresnel interactions. Such high index narrowband filters provide low angle sensitivity for the wavelength selective reflectors thus allowing different signals' frequencies to be spaced as closely as about 1 nm (about 125 GHz) and at the same time keeping the field of view as wide as approximately 10 degrees.

Fig. 10 illustrates the functioning of holographic optical elements, which may be used to implement deflectors (HOE deflectors) as an alternative or in addition to wavelength selective reflectors in embodiments of this invention.

Holographic optical elements (HOE) are constructed by photorefractive imprinting of a periodic structure within a glass substrate and can produce chromatically-dependent bending of light. Their basic operation is similar to a diffraction grating with the exception that the holographic element can operate in transmission instead of reflection. HOEs can have extremely narrow spectral features. They may be produced using photothermorefractive glass (PTRG) technology which provides high spectral efficiency and may be used for wavelengths near 1550 nm.

The operation of a transmission-mode HOE is shown in Fig. 10. Laser beams at two different input wavelengths are incident upon the device in the vicinity of normal incidence. λ_1 (for example, 1550 nm) is Bragg-matched to the grating so that it is diffracted by the HOE, while λ_2 (for example, greater than 1560 nm or less than 1550 nm) is far enough outside of the HOE's spectral zone of selectivity so that it passes through the HOE undeflected. The diagram shows the case where two HOEs are combined into a single glass substrate thus creating a two-dimensional HOE deflector.

A single conventional HOE steers in one plane.

The use of the deflectors such as or similar to HOE deflectors in an embodiment of this invention is shown in Fig. 11. Each deflector 55-57 acts upon a single wavelength channel chosen among λ_1 - λ_N , directing it into the common path. There is an incoming and outgoing signal for each wavelength λ_1 - λ_N , each signal at the same wavelength. The Faraday rotator 53 and half-wave plate 52, acting in combination as a directional rotation module, apply different polarizations to the incoming, received (Rx), and outgoing, transmitted (Tx), signals to isolate them, while eliminating any polarization effects within the wavelength steering deflectors 55-57 by keeping all wavelengths there at a common linear polarization (denoted as S). A quarter wave plate 51 transforms the linearly polarized waves into right hand circularly (RHC) polarized waves passing through the aperture. The PBS 54 separates the received and transmitted signals which are polarized within orthogonal planes P and S on the right side of the DRM 52-53 and have a common polarization S on the signal path 300.

The advantages of this transmission-mode approach over the reflection-mode bandpass filter approach described above include fewer optical components and no direct retroreflections which improves isolation. Furthermore, the transmission-mode operation also allows one to neglect the polarization effects of the HOE within HOE deflectors and operate with undefined, arbitrary polarizations.

Another embodiment of this invention using HOE devices to steer wavelengths, as shown in Fig. 12, increases the number of channels by using orthogonal polarizations. In this setup, waves with different linear polarizations (denoted as P and S) are steered either by the deflectors 55-57 or deflectors 58-60. Each of the deflectors 55-60 may contain individual HOEs that deflect the appropriate wavelength. The PBS 83 separates received signals and joins transmitted signals of orthogonal linear polarization. Directional rotation modules composed of HWP 52 and FR 53 and HWP 80 and FR 81 change the polarization of signals depending on their direction and allow use of PBS 82 and PBS 54 for separating and joining transmitted and received signals Tx and Rx before and after they traverse the signal paths 300 and 301.

Deflectors 57 and 60 may be referred to as front deflectors, while deflectors 55 and 58 may be referred to as back deflectors.

Fig. 13 shows an embodiment of this invention similar to the embodiment shown in Fig. 5. The components absent in Fig. 5 include the following elements employed for precise aiming and tracking of the signals outside the device: nutating fiber coupling systems, 201 and 202, mirrors applying point ahead angle to compensate for relative motion between terminals, 203 and 204, quad-area detectors, 205 and 206, fast steering mirror for removing mechanical jitter, 207, wide area detector for acquisition, 208, large steering mirror pointing to the general theater of operation, 210. Directional rotation modules 211 and 213 composed of half-wave plates and Faraday rotators change the polarization of signals depending on their direction and allow the use of PBS 212 and PBS 214 for separating and joining transmitted and received signals.

Fig. 14 illustrates additional possible uses of directional rotation modules in embodiments of this invention. The directional rotation module composed of HWP 221 and FR 222 gives in combination with QWP 19 opposite (LHC and RHC) circular polarizations to the received and transmitted signals handled by the same reflector (chosen among 61-68) for the same target. This provides additional isolation between such signals. The directional rotation module 221-222 gives orthogonal polarizations on 103" to any two signals with identical linear polarization moving in opposite directions along 103'.

The directional rotation module composed of HWP 223 and FR 224 may take the role of the directional rotation modules 211 and 213 of Fig. 12.

As can be seen from the above description, embodiments of this invention may use a single aperture to provide significant size, weight, power, and cost reductions for airborne, spacecraft, and terrestrial applications. The directional rotation module combined with a wavelength steering mirror assembly provides polarization division multiplexing of channels and high optical isolation between transmit and receive channels and reduces hardware requirements by redundant use of components. The optical bandpass filter with low sensitivity to angle-of-incidence allows a high number of arbitrarily pointed WDM channels. The terrestrial network applications of this invention exist in dense urban areas where fiber deployment is impractical and/or expensive. The specific applications of this invention include network nodes, relay links between points of presence, and wavelength and polarization routing switches. In all these cases aperture sharing has the advantages of reduced cost, rapid provisioning, and more efficient utilization of size, weight, and power.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.